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Cyclic Spin Testing of Superalloy Disks With a Dual Grain Microstructure

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Introduction

As operating temperatures of gas turbine engines increase, there is a need for superalloy turbine disks which can operate with rim temperatures in excess of 1300 °F. To meet this need, a new generation of nickel-base superalloys, such as ME3, Alloy 10, and LSHR, has been developed (refs. 1 to 3). These alloys all contain a high percentage of gamma prime precipitates, Ni_3Al, and refractory element additions to achieve strength at temperature. Although they provide advantages over older alloys, the continuing need for high tensile strength at intermediate temperatures in the bore of a disk, which runs much cooler than the rim, as well as high creep strength in the rim also demands innovative heat treatments which can optimize bore and rim properties. Traditional heat treatments produce fine grain disks when the solution temperature is maintained below the gamma prime solvus or coarse grain disks when the solution temperature is maintained above the gamma prime solvus. Fine grain disks yield high strength at intermediate temperatures, while coarse grain disks yield high creep strength at elevated temperatures. Recently, several advanced heat treatment technologies (refs. 4 to 6) have been developed which can produce a superalloy disk with fine grain bore and coarse grain rim. Trade studies by GEAE (ref. 7) and AADC (ref. 8) have identified potential advantages offered by superalloy disks which employ a dual grain structure for advanced gas turbine engine application. The GEAE report cited a fatigue benefit for a disk with a dual grain structure when compared with a coarse grain disk, while the AADC report cited a creep benefit for a disk with a dual grain structure when compared with a fine grain disk.

One of the advanced heat treatment technologies for producing superalloy disks with a dual grain structure was developed by NASA to minimize cost and production issues. This process, known as Dual Microstructure Heat Treatment or DMHT, has been demonstrated for a variety of disk shapes and sizes (refs. 9 to 11). Further, the effect of DMHT processing on tensile and creep properties has been demonstrated using test coupons machined from disk forgings as well as spin testing of generic disk shapes (refs. 12 and 13). The purpose of the present investigation is to demonstrate the reliability of the transition zone in a superalloy disk with a dual grain structure under cyclic loading at the component level. In particular, cyclic spin tests of DMHT disks were run to failure and compared with disks given conventional heat treatments at room temperature. Additional cyclic spin tests of DMHT disks were run to failure at an elevated temperature of interest to gas turbine engine application. These test data will be compared with analytical predictions using finite element techniques.

Materials and Procedures

Superalloy disks of LSHR alloy were used in this study. LSHR powder of the composition shown in table 1 was produced by argon gas atomization of vacuum melted ingot. The powder was screened, canned, compacted, and extruded to 6 in. diameter billet. Mults were cut from the billet and isothermally forged to a pancake shape measuring 12 in. diameter and 2 in. thick.

Forgings were then heat treated to produce fine grain, coarse grain, and dual grain structures. Fine grain forgings, approximately ASTM 12, were produced using a conventional subsolvus heat treatment at 2075 °F followed by an oil quench. Coarse grain forgings, approximately ASTM 7, were produced using a conventional supersolvus heat treatment at 2140 °F followed by a fan cool. Forgings with a dual grain structure were produced using NASA's DMHT process at the Ladish Company. The DMHT process is fully described in reference 6 but is summarized here for the reader's convenience. The basic concept behind the DMHT process utilizes the thermal gradient between the interior and exterior of the forging during the initial phase of a conventional heat treatment to develop a dual grain structure. By enhancing the thermal gradient with insulated heat sinks placed on the top and bottom surface of the forging, as shown in figure 1, the desired dual grain structure can be obtained using a conventional gas-fired furnace maintained at a temperature above the gamma prime solvus of the alloy. The forging and heat sink package is place in the hot furnace and removed from the furnace when the outer periphery of the forging has exceeded the solvus but before the center of the forging reaches the solvus, thereby producing the desired dual grain structure. The DMHT forgings used in this study were given a subsolvus solution heat treatment to set the bore grain size before the DMHT processing. The DMHT step was run with a furnace temperature of 2175 °F and lasted about 1 hour. After removal from the furnace, the heat sinks were rapidly removed from the forging, and the bare forging was then quenched in oil. The resulting macrostructure of the DMHT forging is shown in figure 2. Microstructural details of the DMHT forging, grain size and gamma prime distributions, are presented in figure 3 showing a bore grain size of ASTM 12 and a rim grain size of ASTM 6. All forgings were subsequently aged at 1500 °F for 8 hours.

Most of the forgings were machined to the generic disk shape shown in figure 4 for spin testing, however, several forgings were cut up to produce tensile and fatigue test bars to provide data for finite element analysis of the spin tests. This design was developed to produce an extremely high level of loading at each of the four holes in the disk's web. These web holes were positioned to bisect the grain size transition zone of the DMHT disks, thereby producing an aggressive assessment of reliability in the transition region of DMHT disks. All disks were machined using a standard lathe turning process employing carbide tooling. The web holes were cut undersize using EDM and finished to final dimension, 1 in. diameter, with a low stress grind employing a gentle edge break. A photo of a machined disk is presented in figure 5.

All spin testing was conducted at the Balancing Company of Dayton, Ohio. The spin pit employed an air turbine drive system, an electrically heated furnace for elevated temperature testing, and a high temperature arbor shown in figure 6. The arbor design employed a stretch bolt and capture flange to hold the disk at the bore. A more complete description of the spin testing hardware can be found in reference 12. Room temperature cyclic spin tests were run on a fine grain disk, a coarse grain disk, and a DMHT disk. These tests were run with a 3 minute cycle between 1000 and 34000 rpm to failure. Elevated temperature cyclic spin tests were run on DMHT disks at 1300 °F. One test was run between 1000 and 30000 rpm and a second test was run between 1000 and 31000 rpm each with a 3 minute cycle. As before, all tests were run to failure. The rpm levels in all tests were selected to produce test lives between 1000 and 10000 cycles in duration. Tests were interrupted periodically to check for disk growth and cracks.

Results and Discussion

Tensile and fatigue tests were run at room temperature and 1300 °F to support the analysis of the spin tests. The tensile results are summarized in table 2. As expected, the yield strength of the fine grain material is greater than the coarse grain material at both temperatures. The fatigue tests were run under load control to maximum and minimum stress levels spanning the anticipated loading levels in the disks. The fatigue life curves are plotted in figures 7 and 8 using a Smith-Watson-Topper stress parameter. At either temperature, the fine grain data shows a significant life advantage over the coarse grain data, as expected. Further, specimens machined from the transition zone of the DMHT forging, which contain both fine and coarse grain regions, exhibit fatigue lives which are similar to coarse grain material.

The results of the cyclic spin testing run at room temperature and 1300 °F are summarized in table 3. In all tests, growth of the disks was negligible after the first few cycles. The most notable change in disk dimensions was observed at the web holes, the hole diameters growing about 0.001 in. after initial loading. No further changes in disk dimensions were noted during the remainder of the tests. Evidence of cracking before failure was observed in only one disk, tested at 1300 °F and 31000 rpm. It was detected as a result of an increased vibration signature. One crack, about 0.25 inches long, was located at one of the four web holes. All disks failed from fatigue cracks originating at the highly stressed web holes, as seen in figure 9. Ranking of the disk life at room temperatures was in line with expectations; the fine grain disk had the longest life, 12227 cycles, while the coarse grain and DMHT disks exhibited lives which were less than 10000 cycles. At 1300 °F, DMHT disk life was also observed to occur in the intended life range, between 1000 and 10000 cycles.

To gain a further understanding of disk behavior in these tests, elastic-plastic finite element analyses were performed using the commercial Algor™ package. A three-dimensional finite element model of the disk was constructed as shown in figure 10. Isotropic, bilinear, elastic-plastic material behavior was assumed using the properties shown in table 4. Two material groups were used to model the DMHT disk, fine grain bore/web and coarse grain web/rim. For all analyses superalloy density was assumed to be $0.3 lb_m/in^3$ and Poisson's ratio was assumed to be 0.3. Stress and displacement maps were generated as a function of rpm for all disks until response stabilized.

For all tests, disk response was found to stabilize within the first two cycles. Most of the disk exhibited elastic response with the exception of a small region surrounding the web holes. Material in this region flowed at maximum rpm resulting in a compressive stress state at minimum rpm, as seen in figure 11. This resulted in a permanent growth of the web holes on the order of 0.001 in., in line with experimental observation. At room temperature, the response of the fine grain, coarse grain, and DMHT disk were surprisingly similar. However, the peak tensile stress was notably lower for the coarse grain disk, as shown in table 5, while the stress range was similar for all three disks.

As the stress state is multiaxial, analytical fatigue life estimates were made using von Mises stress, σ_v, and the following methodology. Utilizing the peak stresses, at maximum and minimum rpm levels, a Smith-Watson-Topper stress parameter, σ_{swt}, was calculated for the critical element at the web hole using the following expression:

$$\sigma_{swt} = (\sigma_{vmax}(\sigma_{vmax}-\sigma_{vmin})/2)^{0.5}$$

Disk life was estimated by comparing σ_{swt} of the disk with the appropriate uniaxial fatigue data in figure 7 or 8. For the DMHT disks, disk life was assumed to be limited by the coarse grain life data which is significantly less than the fine grain life data. The results of these analyses are presented in figures 12 and 13 along with the experimental life data. At room temperature, figure 12, the analytical and experimental life data are found to be in relatively good agreement. The DMHT is seen to have the lowest life, both analytically and experimentally. Analytically, this result can be explained by a combination of high stresses associated with the fine grain microstructure and lower fatigue life associated with the coarse grain microstructure at the grain size transition zone of the DMHT disk. Comparison of all DMHT tests, figure 13, is relatively good with the exception of the 30000 rpm test at 1300 °F, in which the experimental life data exceeds the predicted life data by a factor of five. Explanation for this result could include routine scatter associated with fatigue data, which often exceeds a factor of two, the conservative philosophy employed in the analytical life prediction, and the omission of any large scale crack growth life assessment for the disk relative to the "small bar" test data in figure 8. This explanation is also bolstered by the fact that all predictions, figures 12 and 13, are less than the experimental life data.

Overall agreement between experimental and analytical fatigue life for the cyclic spin tests was acceptable and indicates that the behavior of the DMHT disk can be predicted to a large extent. Further, one might conclude the fatigue performance of the DMHT disk is inferior to the fine grain disk and to a lesser extent the coarse grain disk. While this is true for this design, actual disk designs would not impose loads of this magnitude in the transition zone by placing large holes at this critical location. In fact, actual disks are often limited by bore fatigue issues, where the fine grain microstructure of the DMHT disk will outperform a coarse grain disk as suggested by the GEAE trade study (ref. 7).

Summary and Conclusions

An aggressive cyclic spin test program was run to verify the reliability of superalloy disks with a dual grain structure, fine grain bore and coarse grain rim, utilizing a disk design with web holes bisecting the grain size transition zone. Results of these tests were compared with conventional disks with uniform grain structures. Analysis of the test results indicated the cyclic performance of disks with a dual grain structure could be estimated to a level of accuracy which does not appear to prohibit the use of this technology in advanced gas turbine engines, although further refinement of lifing methodology is clearly warranted.

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TABLE 1.—COMPOSITION OF LSHR IN W/O

Co	Cr	Al	Ti	W	Mo	Ta	Nb	C	B	Zr
21	13	3.5	3.5	4.3	2.7	1.6	1.5	.03	.03	.05

TABLE 2.—TENSILE DATA FOR DMHT DISK

LOCATION	TEMP (°F)	YIELD (KSI)	UTS (KSI)	ELONGATION (%)
BORE	70	186	251	18
TRANSITION	70	173	237	20
RIM	70	169	228	21
BORE	1300	175	199	6
TRANSITION	1300	166	202	6
RIM	1300	159	198	7

TABLE 3.—OBSERVED DISK LIFE IN CYCLIC SPIN TESTS

DISK	TEMP (°F)	MAX RPM	LIFE (CYCLES)
FINE GRAIN	70	34000	12227
COARSE GRAIN	70	34000	8348
DMHT	70	34000	3042
DMHT	1300	31000	1680
DMHT	1300	30000	5685

TABLE 4.—TENSILE PROPERTIES USED IN THE FINITE ELEMENT ANALYSIS

TEMP (°F)	GRAIN SIZE	E_{ELAS} (KSI)	YIELD (KSI)	E_{PLAS} (KSI)
70	FINE	31000	186	1000
70	COARSE	31000	169	1000
1300	FINE	27000	175	1000
1300	COARSE	27000	159	1000

TABLE 5.—PEAK VON MISES STRESS (KSI) DATA FOR CYCLIC SPIN TESTS. MINIMUM STRESS DATA OCCURS AT 1000 RPM FOR ALL TESTS

DISK	TEMP (°F)	MAX RPM	MAX STRESS	MIN STRESS
FINE GRAIN	70	34000	195	–99
COARSE GRAIN	70	34000	180	–112
DMHT	70	34000	193	–100
DMHT	1300	31000	181	–64
DMHT	1300	30000	180	–50

Note: Minimum von Mises stress assigned a negative value to emphasize compressive stress field at 1000 RPM near periphery of hole.

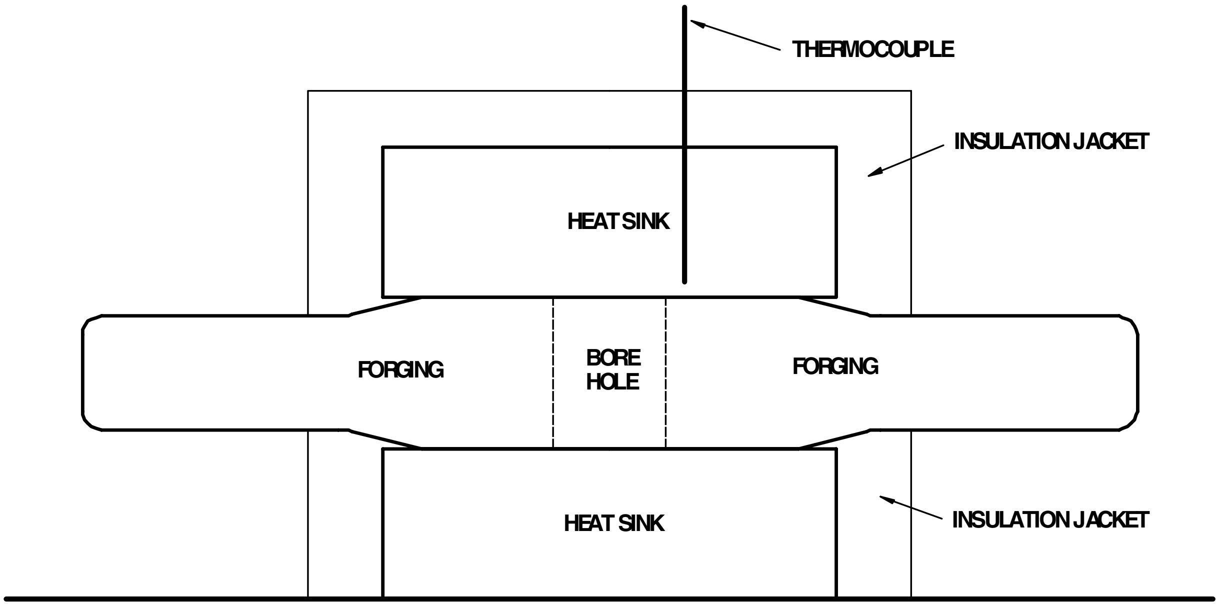

Figure 1.—Forging and DMHT heat sink assembly.

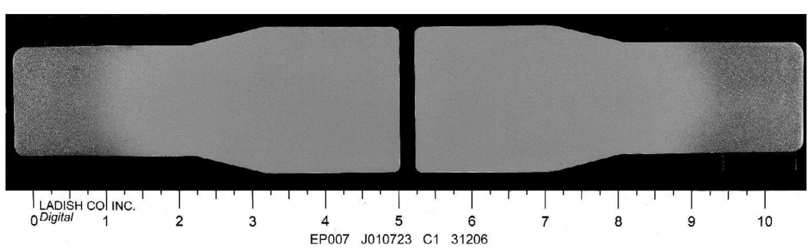

Figure 2.—Macrostructure of DMHT disk.

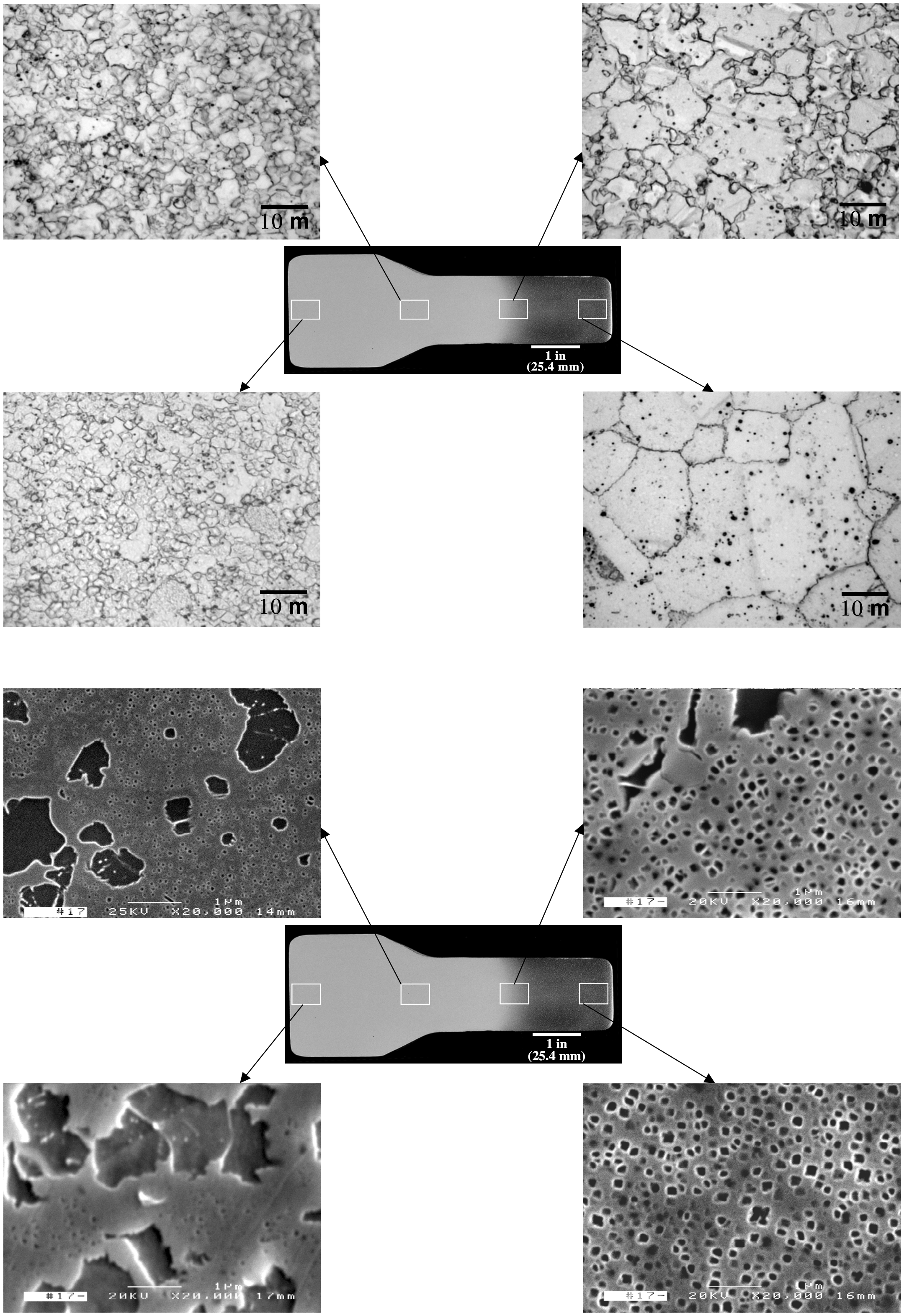

Figure 3.—Grain size (upper) and gamma prime (lower) distribution in DMHT disk.

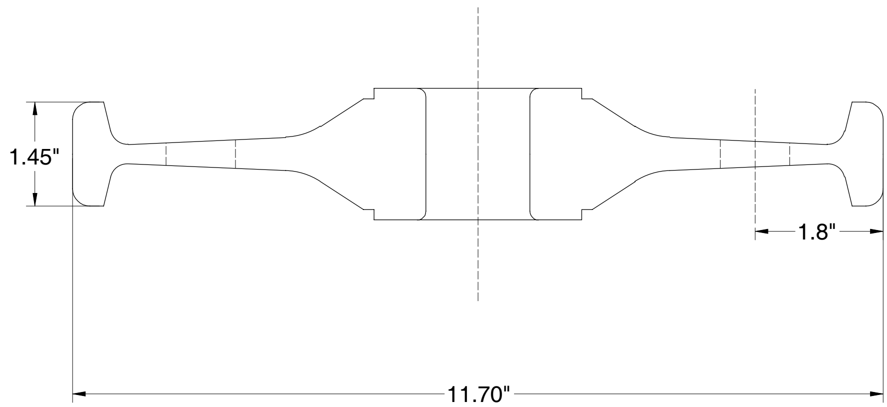

Figure 4.—Disk design for cyclic spin tests.

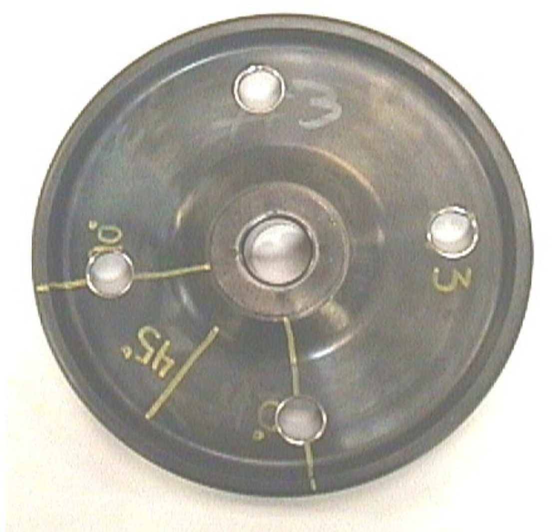

Figure 5.—Photo of machined disk.

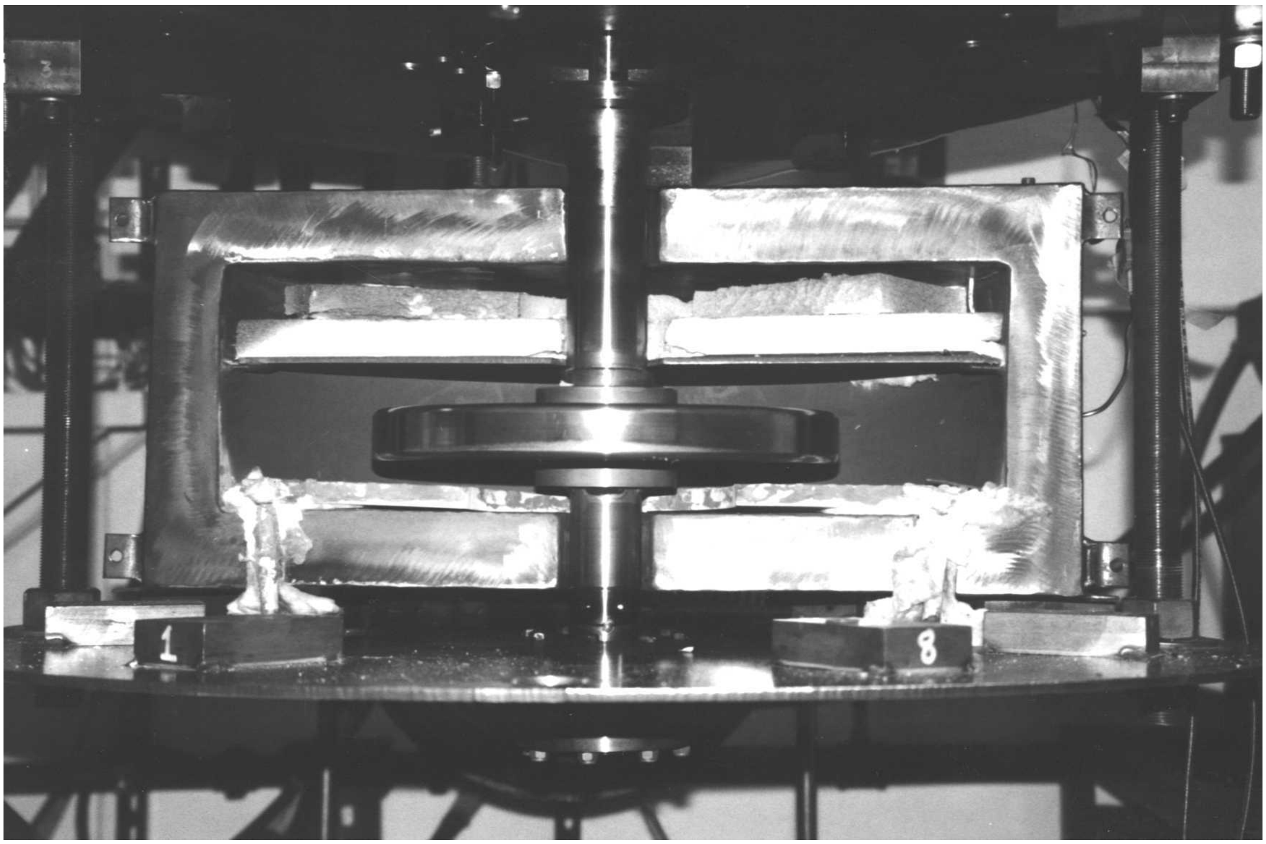

Figure 6.—Photo of disk, arbor, and furnace used for spin testing.

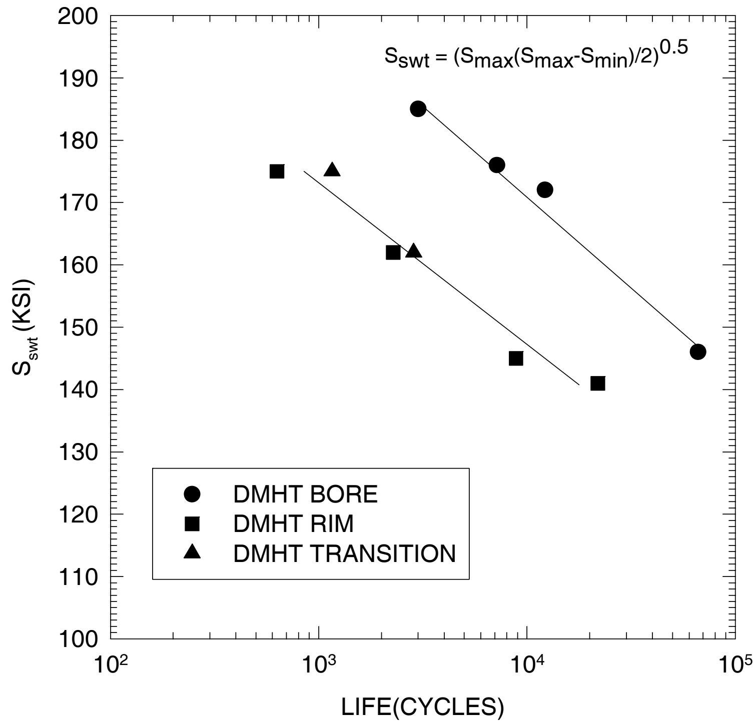

Figure 7.—Room temperature fatigue data.

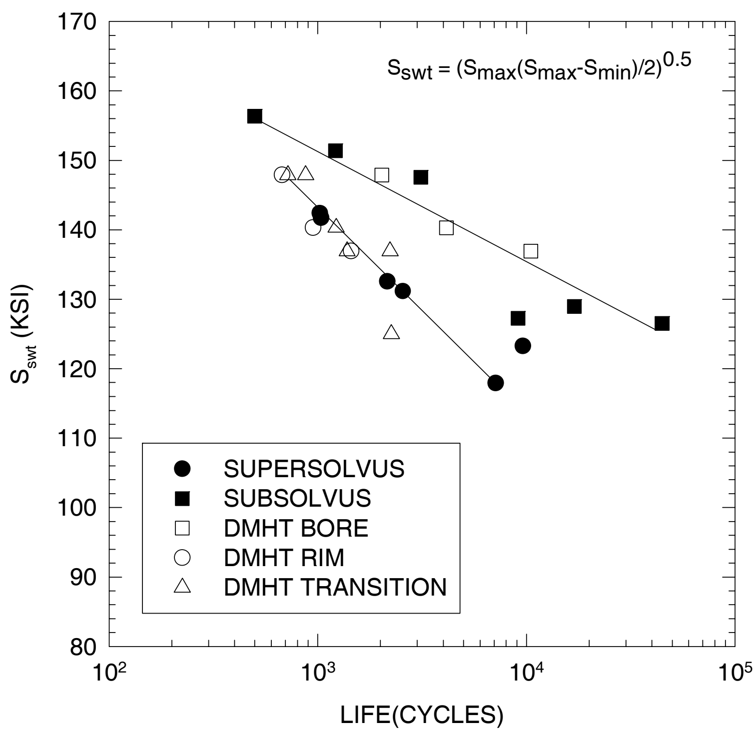

Figure 8.—1300 °F fatigue data.

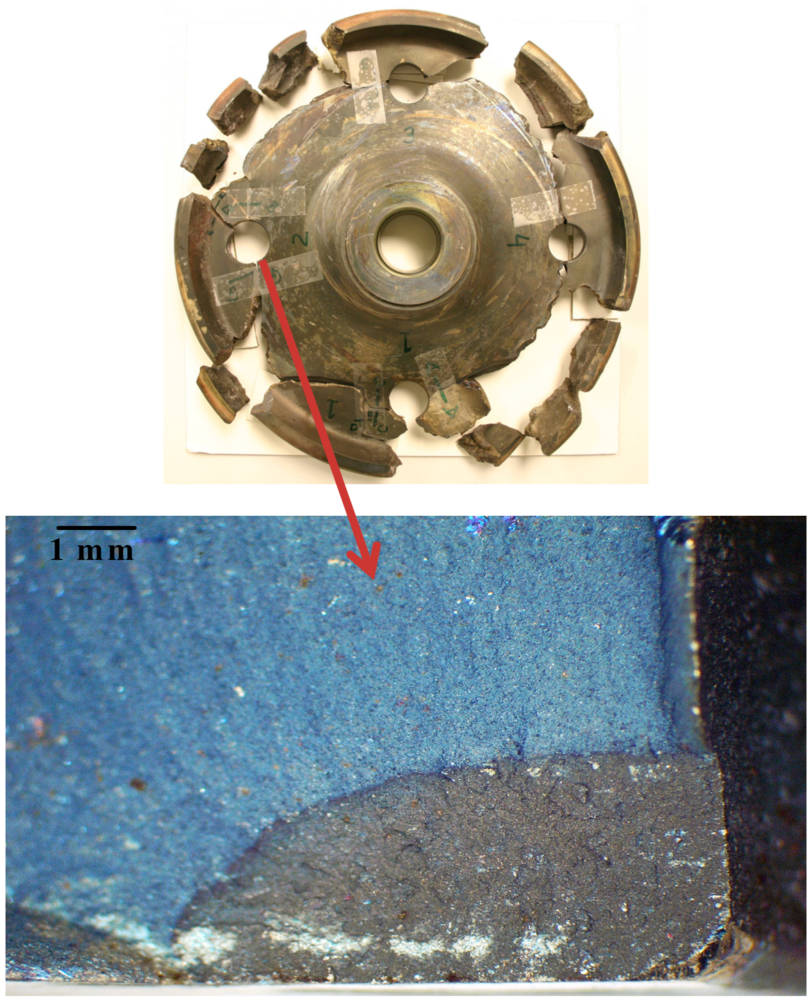

Figure 9.—Fatigue origin in cyclic spin test.

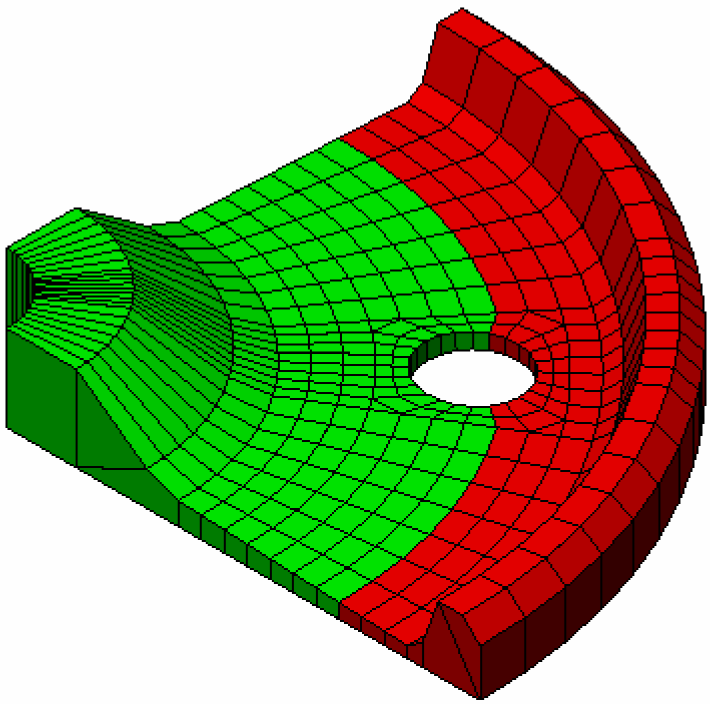

Figure 10.—Finite element model of DMHT disk. Green region represents fine grain microstructure and red region represents coarse grain microstructure.

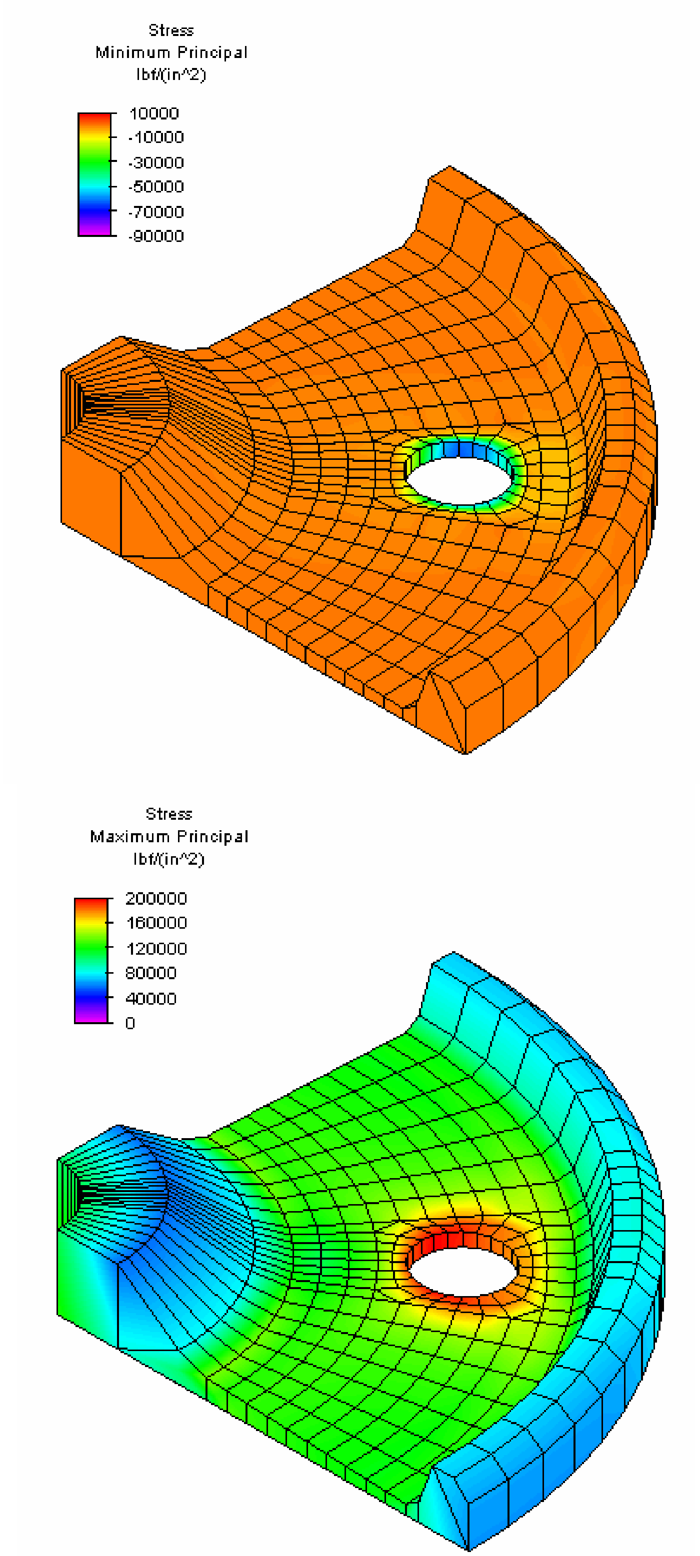

Figure 11.—Maximum principal stress (lower) at 31000 RPM and minimum principal stress (upper) at 1000 RPM for the DMHT disk tested at 1300 °F.

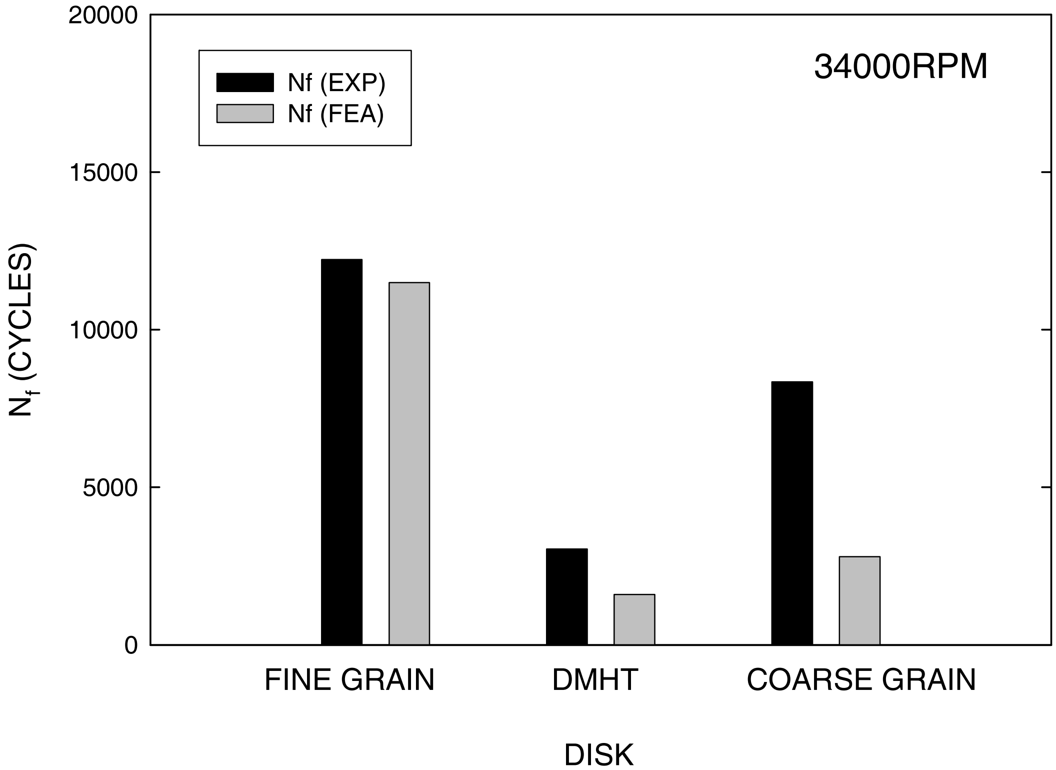

Figure 12.—Comparison of experimental and analytical cyclic spin test results at room temperature.

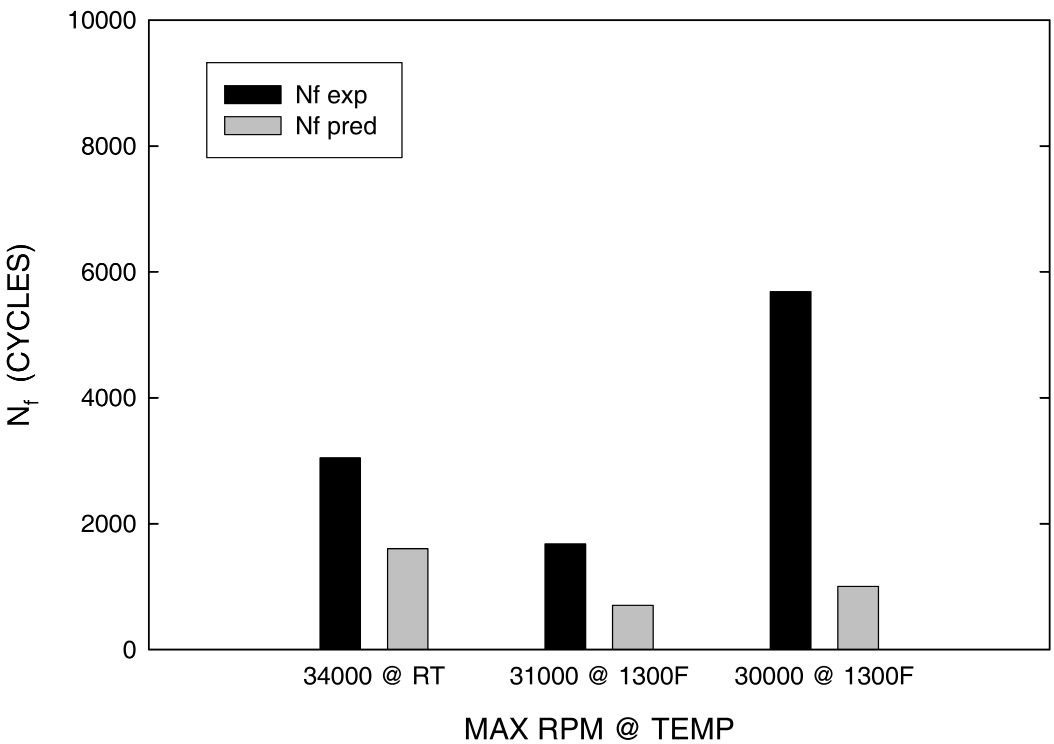

Figure 13.—Comparison of experimental and analytical cyclic spin test results for the DMHT disks.

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